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Modeling the relationship between the urban development and subsurface warming in seven Asian megacities

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ABSTRACT

The authors used a mesoscale climate model, CSU-MM and digital land-use data from seven Asian megacities to simulate ground surface temperature (T_{sfc}) related to urbanization for three discrete years of the 20th century. The variability of T_{sfc} was compared with the measured vertical profiles of subsurface temperature in the targeted megacities, which were expected to record the historical time-series of T_{sfc}. Considering a calm and clear day of the hottest season, results showed that T_{sfc} increased about 1.1 K 100 y^{-1} during the 20th century. Considering the seasonal climate variability, simulations were run for three additional cases (rainy day in the hottest season; clear day and rainy day in the coldest or rainy season) for each year in each megacity. The difference between the rates of change of T_{sfc} in Bangkok (0.9 K 100 y^{-1}) and Tokyo (1.9 K 100 y^{-1}) is considerable, which suggests that the differences of annual climatic variability are important for the analyses of urban subsurface warming. The authors conclude historical digital land-use data are useful to study past urban climate change in numerical simulation, and difference of annual climatic variability brings the difference of subsurface warming in each megacity.

1. Introduction

1.1. Problem presentation

About 120 years have passed since meteorological observations began in Asia; since then, researchers have used a variety of methods to reconstruct the climate of earlier times. One such method has been to use notations about weather in ancient documents and journals. Since the early modern times, the Japanese have left many usable records, and, although these are mostly qualitative accounts, researchers have learned how hot in summer, or how cold in winter, it was in the past. Although the information collected from these documents contains many temporal and spatial gaps, recent advances in computerized meteorological modeling have made it possible to compute local distributions of climatologic parameters; for example, the distribution of surface air temperature (T_a) is determinable if the surface boundary conditions, like the land-use distributions, are known (Ichinose, Shimodozono, & Hanaki, 1999; Kimura and Takahashi, 1991). Ichinose (2003) used numerical simulations with a mesoscale climate model referenced to digital land-use data (2 km grid) covering all of Japan to attempt to isolate the influence on T_a of regional warming related to land-use change during a recent 135-year period. During this period, areas of regional warming related to changes of land use expanded around Tokyo and Osaka. However, validation of the results of this study was difficult because of the limited amount of available data on long-term climate fluctuations.

To validate the results of modeling such as that of Ichinose (2003), observed climatologic data (e.g., air temperature) are needed to provide initial values for the modeling. The network of weather stations and other observation facilities that has been established throughout Japan since 1876 provides long-term temperature fluctuations to the present day. Data for Tokyo in particular have often been used to associate changes in urban climate in conjunction with urbanization (Yoshino, 1990/1991). Many instances of global warming (Jones, 1988) and changes of air temperature due to the regional climate change have been identified over broader areas and longer periods than those caused by local land-use changes (Maejima et al., 1980); comparing these to modeled temporal changes in air temperatures may elucidate the contribution of land-use change to climate change in Japan. Comparisons like this will also help to overcome the problem of temporal and spatial discontinuity in historical climatologic information.

Another reason such research is important in Japan is that

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urbanization in large Japanese cities has increased local air temperatures by about 1 °C during the latest century (Fujibe, 1995). Until now researchers have relied on statistical methods to distinguish between the influence on air temperature of localized warming caused by urbanization, and the influence of global warming and other broader scale changes of air temperature (Kato, 1996). Of course, such methods cannot be applied to regions or time periods for which there are no observed data. Much pioneering research has eliminated the influence of urbanization as noise when estimating temperature changes over large areas (Kukla, Gavin, & Karl, 1986). Use of a mesoscale model with past land-use distributions as surface boundary conditions to simulate past climatologic parameters (e.g., air temperature distributions) might help to distinguish the influence of localized warming due to urbanization from that of global warming and regional-scale (e.g. Far East Region, Eastern Asia, Japan and Chinese Coastal Area etc.) fluctuations of air temperature for regions and time periods lacking observed data (Ichinose, 2003). Certainly, the mesoscale and urban-scale meteorological model have been widely used in other studies, such as Kusaka et al. (2012) and Doan, Kusaka and Ho (2016), which created the Weather Research and Forecasting Model (WRF) to examine the phenomena of urban climate in different scales. This WRF is one of the newest models as so far, powered by the super computer technology. However, Kusaka's model still needs to be improved especially on the respect of human activity affect and urban concentration, which the authors are focusing on.

Case studies of the area around the upper reaches of the Rhine River as it was in 1710 (Lenz, 1996) and of the Edo area (Tokyo was called "Edo" until the middle of the 19th century) during the first half of the 19th century (Ichinose, 2003) are examples of attempts to quantify the influence of urbanization-induced changes in the surface heat budget on surface air temperatures, as opposed to research from a historical climatology perspective. These researchers derived land-use distributions for the periods they studied from historical maps and other historical sources. Because the periods they studied pre-date the keeping of meteorological records, comparisons with observed meteorological data are not possible. The results of a similar study by Kusaka, Kimura, Hirakuchi, & Mizutori (2000) in the Tokyo region (the Kanto Plain) for c. 1985, c. 1950, and c. 1900 agree well with those of Ichinose (2003).

1.2. Research background and purpose

Because subsurface temperatures are affected by surface warming (heat of the ground level is conducted downwardly), the vertical profile of subsurface temperature obtained from boreholes can be used to determine past ground surface temperatures (T_{sfc}) (Huang, Pollack, & Shen, 2000; Lewis, 1992; Pollack, Huang, & Shen, 1998). Such depth profiles preserve past temperature gradients, which can be used in the reconstruction of past climate (Cermak, 1971; Lanchenbruch & Marshall, 1986; Pollack & Chapman, 1993; Pollack & Huang, 2000; Taniguchi, Shimada, & Uemura, 2003; Wang, 1992). Past ground surface temperatures derived from subsurface temperature profiles for four Asian cities over the last 100 years agree with air temperature records in those cities (Taniguchi, Uemura, & Jago-on, 2007). Subsurface temperature profiles can also provide important information for separating the effects of urbanization and global warming on groundwater systems.

Agreement of past values of T_{sfc} computed in the time periods of meteorological observations with T_{sfc} estimated for the same period from vertical profiles of subsurface temperature supports the validity of numerical simulations applied to periods before the start of meteorological observations based on the theory suggested by Huang et al. (2000). Moreover, when T_{sfc} during pre-observation periods is reconstructed from vertical profiles of subsurface temperature, estimation of the past annual average surface air temperature (T_a) is possible, because the main cause of variability of T_a (apart from air mass advection) is variability of T_{sfc} due to heat exchange at the ground surface (Huang et al., 2000). "Vertical profile of borehole temperatures" is the only available (observable) data to evaluate the (effect of) past T_{sfc}. Therefore, observing it is the best way for estimating the behavior of the past T_{sfc}. The authors assume that delta T_{sfc} (i.e. warming) between targeted two stages and the subsurface warming (expected from vertical profile of borehole temperatures) has a proportional relationship. Therefore, the authors regard that T_{sfc} represents the subsurface warming. In this model, computed T_{sfc} is defined at the center depth of the primary subsurface grid (vertical size: 1 cm), so the temperature at 0.5 cm below the ground surface is computed and given as this T_{sfc}. Increases of surface air temperature are not as strong as those of ground surface temperature derived from subsurface temperature profiles, because heat conduction in the subsurface is much slower than heat convection in the air above the ground surface (Huang, Taniguchi, Yamano, & Wang, 2009).

The "heat island effect" due to urbanization has contaminated the subsurface thermal regime in many cities (Miyakoshi, Hayashi, Monyrath, Lubis, & Sakura, 2009; Taniguchi et al., 2003). Safanda, Rajver, Correia and Dedecek (2007) attributed a peculiar increase in subsurface temperature at a monitoring station in Prague to recent surface construction near the station. Taniguchi, Burnett and Ness (2009a) and Taniguchi, Shimada, Fukuda, Yamano, Onodera et al. (2009a) described subsurface temperature anomalies caused by the heat island effect on the basis of measured vertical profiles of subsurface temperature in Asia. Taniguchi and Uemura (2005) analyzed borehole temperature profiles in the Osaka area and inferred from the shape of the profiles that the magnitude of recent surface warming was much larger in the city center than in suburban Osaka. Taniguchi, Shimada, Fukuda, Yamano, Onodera et al. (2009b) showed that the heat island effect on subsurface thermal regimes in urban areas in Asia decreases exponentially with distance from the city center.

Certainly, unlike this study, closely related works on urban subsurface (i.e. ground surface) temperature and groundwater temperature which are not modeled but correlated from remotely sensed maps (e.g. Zhan et al., 2014, Benz, Bayer, Goettsche, Olesen, & Blum, 2016) are present, as well as recent work on long-term evolution of subsurface urban heat islands based on observed data (Menberg, Blum, Schaffitel, & Bayer, 2013). Zhan et al. (2014) and Benz et al. (2016) examined the urban subsurface temperature and groundwater temperature by using the remote sensing approach. However, these studies cannot prove a reference of revealing the historical changing of the urban climate (including urban subsurface temperature), because the previous remote sensing data is impossible to obtain before the launch of satellite. Unlike these studies, the authors are focusing on both the past T_{sfc} of 100 years ago and the current one, in order to clarify the relationship between the urban development and subsurface warming in seven Asian megacities based on the numerical simulation of urban climate, considering the land-use data in these megacities for three discrete years of the 20th century.

In this study, the authors used the Colorado State University Mesoscale Model (CSU-MM) (Pielke, 1974; Ichinose, 2003) and digital land-use data (2 km grid) from seven Asian megacities (Seoul, Tokyo, Osaka, Taipei, Bangkok, Manila, and Jakarta) to simulate T_{sfc} for three discrete years of the 20th century. As mentioned in Section 1.1, this paper used this CSU-MM for the mesoscale urban simulation instead of the WRF model, because using the CSU-MM is enough for the computing of this paper and the purpose has been realized successfully. The land-use data (Fig. 1) were established by Research Institute for Humanity and Nature (RIHN). Moreover, Taniguchi, Burnett and Ness (2009b) used these data for the project of "Human Impacts on Urban Subsurface Environments". Then, same data were used by this paper in numerical simulations of urban subsurface warming related to recent urbanization in the seven cities in a project for which borehole temperatures were logged in the cities and surrounding areas. Taniguchi, Burnett and Ness (2009b) recognized the effects of recent surface warming in the shapes of most of the temperature profiles obtained, and

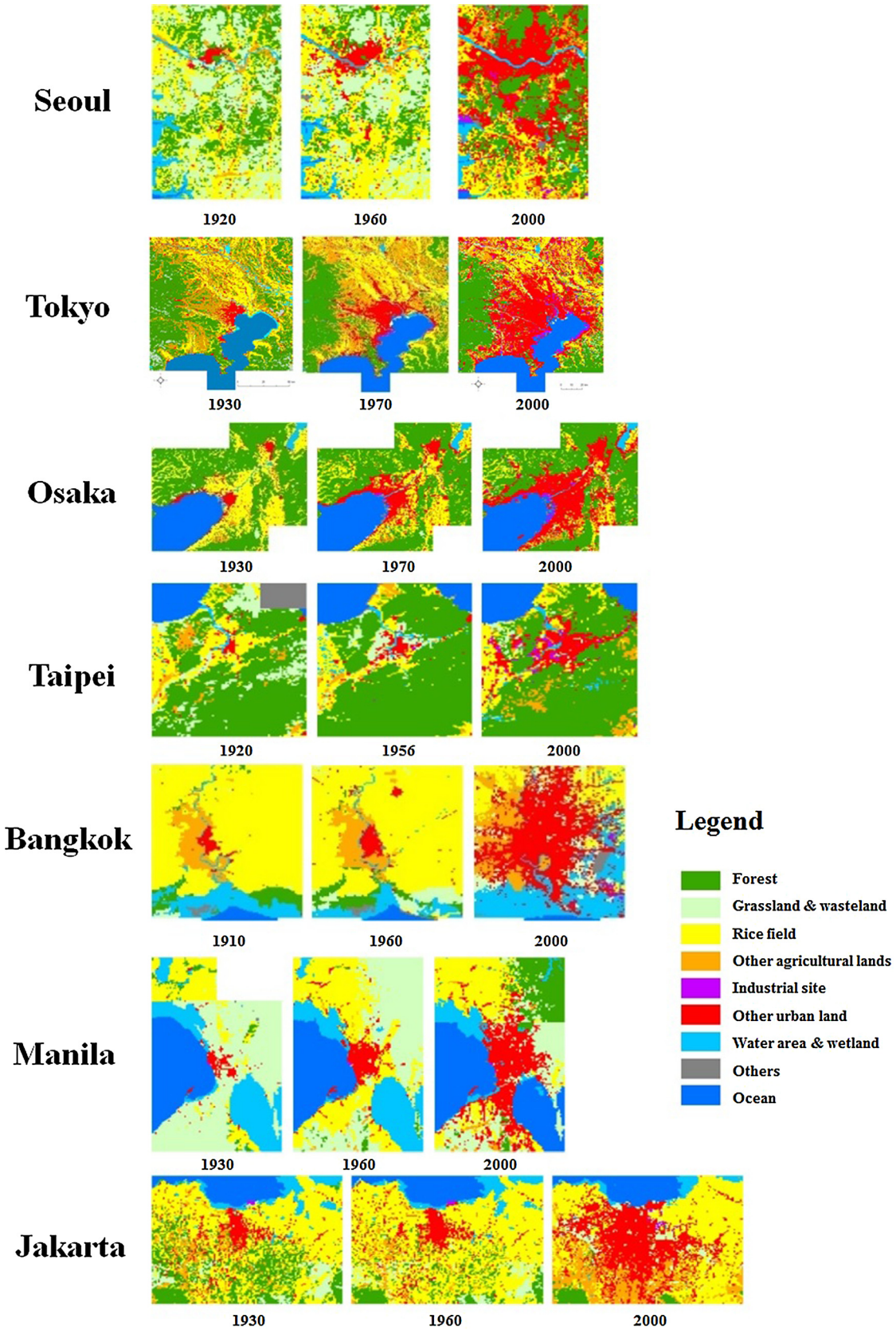

Fig. 1. Urbanization around seven megacities in Asia (RIHN Research Project C-5 "Human Impacts on Urban Subsurface Environments"). *Note: The original data are in 500 m square grid cells. Data source can be checked from the homepage of RIHN Archives.* http://archives-contents.chikyu.ac.jp/751/Bangkok_landuse_raster.zip (Bangkok). http://archives-contents.chikyu.ac.jp/752/Jakarta_landuse_raster.zip (Jakarta). http://archives-contents.chikyu.ac.jp/753/Manila_landuse_raster.zip (Manila). http://archives-contents.chikyu.ac.jp/754/Osaka_landuse_raster.zip (Osaka). http://archives-contents.chikyu.ac.jp/755/Seoul_landuse_Seoul.zip (Seoul). http://archives-contents.chikyu.ac.jp/756/Taipei_landuse_raster.zip (Taipei). http://archives-contents.chikyu.ac.jp/757/landuse_Tokyo.zip (Tokyo).

the time-series borehole data provided information on the mechanism of heat transfer (conduction) and thermal diffusivity (Yamano et al., 2009). Taniguchi, Burnett and Ness (2009b) also showed that the depth at which the subsurface temperature profile departs from a steady geothermal gradient increases with the magnitude of the surface warming (including the heat island effect) and with the elapsed time since the start of the anthropogenic surface warming. Land-use distributions based on historic maps and other historic sources were also produced by Taniguchi, Burnett and Ness (2009b) for the periods studied; because those periods pre-date the age of meteorological observations, there can be no comparison with observed meteorological data. Therefore, the variability of T_{sfc} simulated by using these data as surface boundary conditions was compared with the measured vertical profiles of subsurface temperature in the targeted megacities (Taniguchi et al., 2007, 1999; Taniguchi, Shimada, Fukuda, Yamano, Onodera et al., 2009b; Yamano et al., 2009; Lubis et al., 2009; Hamamoto et al., 2009), which were expected to record the historical time-series of T_{sfc}.

Taniguchi et al. (2007) identified surface warming during the last century of 2.8 °C in Tokyo and 1.8 °C in Bangkok. The seven land-use data sets revealed the major characteristics of land-use change during the 20th century expansion of urbanized areas in the seven megacities considered here (Fig. 1). Such large-scale surface changes would be expected to bring about localized climatic changes in response to the resultant changes to the surface heat budget. The aim of this study, therefore, was to quantify the subsurface warming brought about in those seven megacities by changes of land use in the early modern times.

2. Data set and methodology

2.1. Preparation of land-use data

Numerical simulations require the translation of land-use data into surface parameters. Following the methods of Anthes, Hsie and Kuo (1987), Ichinose et al. (1999) assigned values of six surface parameters (albedo, evaporation efficiency, roughness length, density of material covering the ground, specific heat capacity, heat diffusion coefficient) to 10 land-use categories (rice paddies, vegetable fields, orchards, lawns and parks, forests, yards, built-up areas, traffic use, other use, and surface water) on the CSU-MM, which is used in this study. For each megacity, land use data (Taniguchi, Burnett, & Ness, 2009b; Fig. 2) was assigned to the nearest one of 10 categories shown above.

Urbanized areas (i.e. built-up areas and areas of traffic use) were assumed to generate anthropogenic heat. Changes of diurnal irradiance in each megacity were based on a daily average of 30 W m^{-2} in the hottest season of 2000 according to the method of Ichinose et al. (1999). Intensity of anthropogenic heat generation at the beginning of the 20th century was set at 50% of that in 2000 (after Ichinose (2003)).

2.2. Modeling overview

The model used for numerical simulation in this study is based on the CSU-MM (Pielke, 1974) with minor modifications (Ulrickson and Mass, 1990; Kessler and Douglas, 1992) and slight differences in some surface boundary conditions used (e.g., albedo or anthropogenic heat in each grid cell (Ichinose et al., 1999)). Hydrostatic equilibrium and the Boussinesq approximation are assumed in this model. The model includes equations of motion, moisture, and continuity within a three-dimensional terrain-following coordinate system and includes a thermodynamic equation, a diagnostic equation for pressure, and an equation for surface heat budget. Exchange coefficients are computed from turbulent kinetic energy and turbulent length scale due to Therry and Lacarrere (1983). Planetary boundary layer depth is given with the methodology of Ulrickson and Mass (1990). Energy balance at the surface, including a term for anthropogenic heat, is expressed as:

$$Q = S + I - H - L - C - G + A,$$

where Q is the heat stored in the surface layer of the soil, S is the net shortwave radiation flux at the ground surface, I is the incoming infrared radiation from the atmosphere, H is the sensible heat flux, L is the latent heat flux, C is the outgoing infrared radiation from the surface, G is the heat conducted into the soil layer and A is anthropogenic heat flux. I is calculated considering the influence of only carbon dioxide and moisture. The potential temperature in the soil layer is calculated with a heat conductivity equation.

Simulations were run for each of the seven megacities (areas of 50 km × 50 km to 128 km × 128 km, depending on the size of the city) by using land-use data representing three discrete years at intervals of

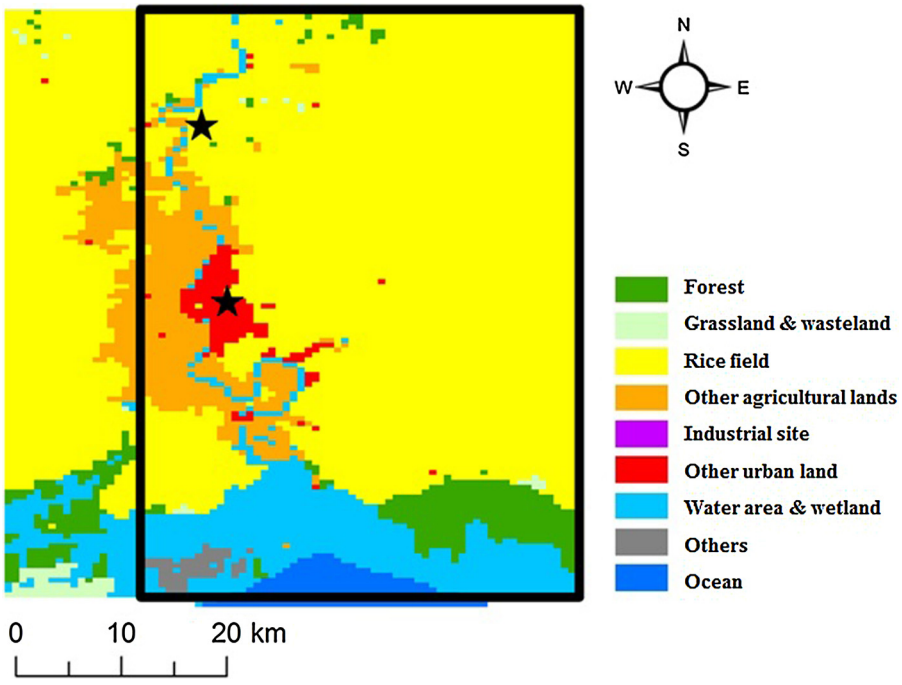

Fig. 2. Example of land-cover/use around Bangkok in 1910 with its legend. *Note: Stars show "City Center" and "Northern Suburb". Inside of solid rectangle line shows the areas displaying computed results in* Fig. 3.

Table 1
List of the initial values for computing.

City	Year	Season	Weather	Land T_{sfs} (K)	Sea T_{sfs} (K)	WD (deg.)	S.A.P. (hPa)	RH (%)	RF	V.G.P.T. (K/km)	Julian day
Tokyo	2000	summer	dry	300.0	300.0	180	1000	75	0.9	5.5	210
Tokyo	2000	summer	wet	300.0	300.0	180	1000	75	0.3	5.5	210
Tokyo	2000	winter	dry	278.0	282.0	315	1010	60	0.9	6.0	30
Tokyo	2000	winter	wet	278.0	282.0	315	1010	60	0.3	6.0	30
Tokyo	1930	summer	dry	300.0	300.0	180	1000	75	0.9	5.5	210
Tokyo	1930	summer	wet	300.0	300.0	180	1000	75	0.3	5.5	210
Tokyo	1930	winter	dry	278.0	282.0	315	1010	60	0.9	6.0	30
Tokyo	1930	winter	wet	278.0	282.0	315	1010	60	0.3	6.0	30
Osaka	2000	summer	dry	302.0	302.0	180	1000	70	0.9	5.5	210
Osaka	2000	summer	wet	302.0	302.0	180	1000	70	0.3	5.5	210
Osaka	2000	winter	dry	280.0	284.0	315	1010	65	0.9	6.0	60
Osaka	2000	winter	wet	280.0	284.0	315	1010	65	0.3	6.0	60
Osaka	1930	summer	dry	302.0	302.0	180	1000	70	0.9	5.5	210
Osaka	1930	summer	wet	302.0	302.0	180	1000	70	0.3	5.5	210
Osaka	1930	winter	dry	280.0	284.0	315	1010	65	0.9	6.0	60
Osaka	1930	winter	wet	280.0	284.0	315	1010	65	0.3	6.0	60
Seoul	2000	summer	dry	298.5	298.5	180	1000	60	0.9	5.5	210
Seoul	2000	summer	wet	298.5	298.5	180	1000	60	0.3	5.5	210
Seoul	2000	winter	dry	275.0	279.0	315	1015	50	0.9	6.0	60
Seoul	2000	winter	wet	275.0	279.0	315	1015	50	0.3	6.0	60
Seoul	1920	summer	dry	298.5	298.5	180	1000	60	0.9	5.5	210
Seoul	1920	summer	wet	298.5	298.5	180	1000	60	0.3	5.5	210
Seoul	1920	winter	dry	275.0	279.0	315	1015	50	0.9	6.0	60
Seoul	1920	winter	wet	275.0	279.0	315	1015	50	0.3	6.0	60
Taipei	2000	summer	dry	303.0	303.0	359	1000	70	0.9	5.5	210
Taipei	2000	summer	wet	303.0	303.0	359	1000	70	0.3	5.5	210
Taipei	2000	winter	dry	289.0	291.0	270	1015	80	0.9	6.0	30
Taipei	2000	winter	wet	289.0	291.0	270	1015	80	0.3	6.0	30
Taipei	1920	summer	dry	303.0	303.0	359	1000	70	0.9	5.5	210
Taipei	1920	summer	wet	303.0	303.0	359	1000	70	0.3	5.5	210
Taipei	1920	winter	dry	289.0	291.0	270	1015	80	0.9	6.0	30
Taipei	1920	winter	wet	289.0	291.0	270	1015	80	0.3	6.0	30
Bangkok	2000	dry	dry	304.0	304.0	180	1000	70	0.9	5.5	90
Bangkok	2000	dry	wet	304.0	304.0	180	1000	70	0.3	5.5	90
Bangkok	2000	rainy	dry	301.0	301.0	180	1000	80	0.9	5.5	270
Bangkok	2000	rainy	wet	301.0	301.0	180	1000	80	0.3	5.5	270
Bangkok	1910	dry	dry	304.0	304.0	180	1000	70	0.9	5.5	90
Bangkok	1910	dry	wet	304.0	304.0	180	1000	70	0.3	5.5	90
Bangkok	1910	rainy	dry	301.0	301.0	180	1000	80	0.9	5.5	270
Bangkok	1910	rainy	wet	301.0	301.0	180	1000	80	0.3	5.5	270
Manila	2000	dry	dry	303.0	303.0	180	1000	70	0.9	5.5	120
Manila	2000	dry	wet	303.0	303.0	180	1000	70	0.3	5.5	120
Manila	2000	rainy	dry	301.0	301.0	180	1000	80	0.9	5.5	300
Manila	2000	rainy	wet	301.0	301.0	180	1000	80	0.3	5.5	300
Manila	1930	dry	dry	303.0	303.0	180	1000	70	0.9	5.5	120
Manila	1930	dry	wet	303.0	303.0	180	1000	70	0.3	5.5	120
Manila	1930	rainy	dry	301.0	301.0	180	1000	80	0.9	5.5	300
Manila	1930	rainy	wet	301.0	301.0	180	1000	80	0.3	5.5	300
Jakarta	2000	dry	dry	302.0	302.0	359	1000	70	0.9	5.5	210
Jakarta	2000	dry	wet	302.0	302.0	359	1000	70	0.3	5.5	210
Jakarta	2000	rainy	dry	300.0	300.0	359	1000	80	0.9	5.5	30
Jakarta	2000	rainy	wet	300.0	300.0	359	1000	80	0.3	5.5	30
Jakarta	1930	dry	dry	302.0	302.0	359	1000	70	0.9	5.5	210
Jakarta	1930	dry	wet	302.0	302.0	359	1000	70	0.3	5.5	210
Jakarta	1930	rainy	dry	300.0	300.0	359	1000	80	0.9	5.5	30
Jakarta	1930	rainy	wet	300.0	300.0	359	1000	80	0.3	5.5	30

Note: T_{sfs} is assumed same as T_a. WD and WS: Wind direction and velocity (0.5 m/s) in all layers; S.A.P.: Surface air pressure; RH: Surface relative humidity; RF: Radiation factor; V.G.P.T.: Vertical gradient of potential temperature. Calculated by the authors in refer to the NCDC (2018) (https://www.ncdc.noaa.gov/).

30–60 years between 1910 and 2000 (Fig. 1).

Simulations were run during the hottest season for 48 h starting at midnight (calm and clear conditions assumed) for each year of each city (Table 1), whose initial values are calculated by the authors based on the climate data source created by the formerly National Climatic Data Center (NCDC) (Now the name is National Centers for Environmental Information (NCEI)). It should be noted that it is naturally right to focus on the simulation values during the hottest season, and furthermore it is available to examine the risk of heatstroke (a kind of feedback from the urban heat island to human health) if this paper performs the simulation towards the hottest season. To ensure that the simulation had stabilized before the analysis, only the last 24 h of simulated data were analyzed, because the primary one cycle of computed diurnal variability includes influence of initial values. The time step for the simulation was 15 s. The vertical coordinate system was the same as that used by Ichinose (2003).

The model requires observed values to be used as initial values for the simulations. Sea surface temperatures and radiation factor, initial values for T_a (and T_{sfc}), surface air pressure, vertical gradient of potential temperature, surface relative humidity, and wind direction and velocity for all layers, were derived from published local climate data (Table 1). Lateral boundary conditions were assumed to have gradients of zero. If the aim of the simulations was to include the effects of global warming and other broad-scale climatic factors, it would be necessary

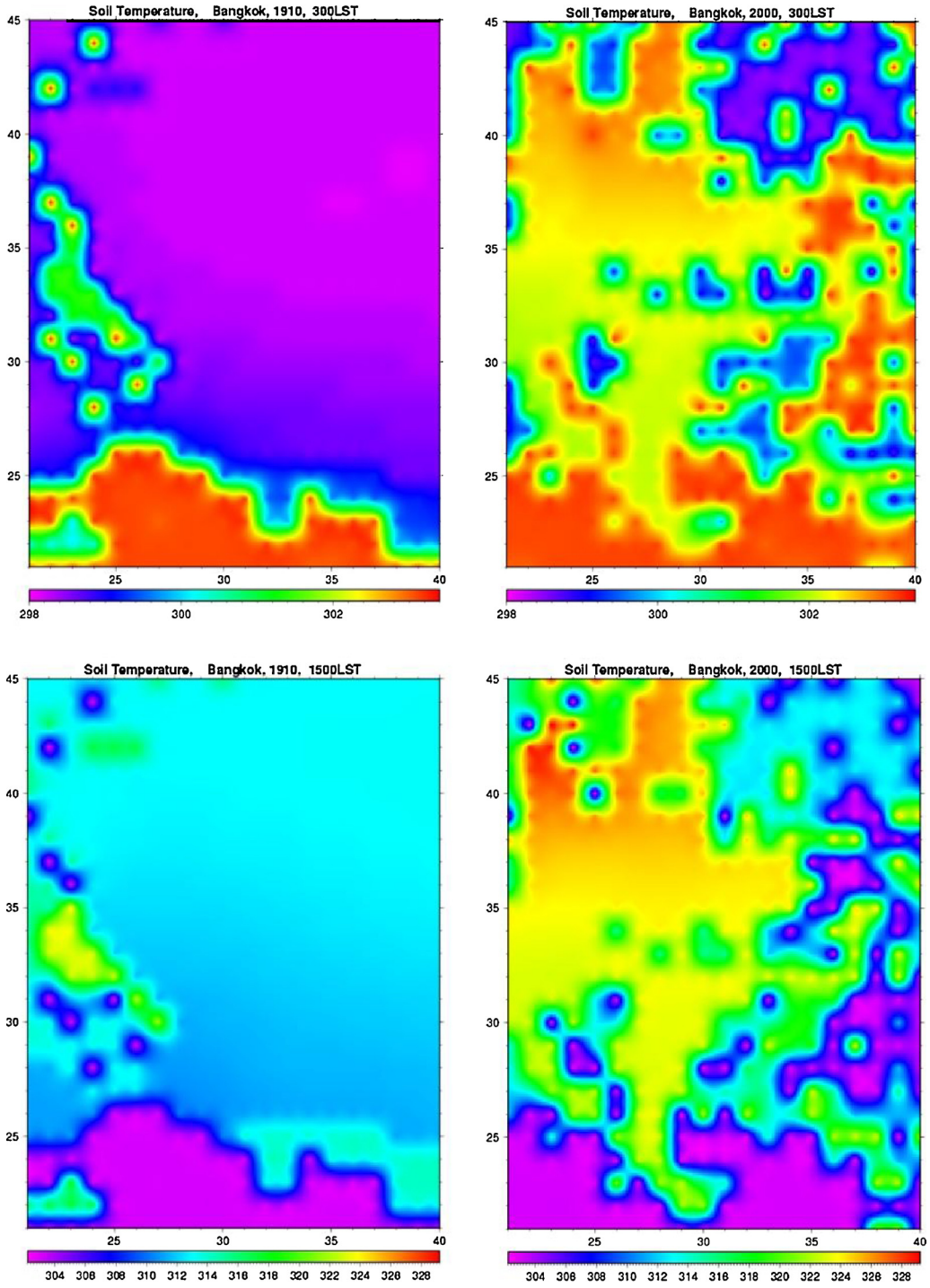

Fig. 3. Computed T_{sfc} (K) around Bangkok in the hottest season (calm and clear day at the end of March). *Note: Upper left: 3 AM in 1910, Upper right: 3 AM in 2000, Lower left: 3 PM in 1910, Lower right: 3 PM in 2000. Temperature ranges are common in the same time zone.*

to vary the initial values. Because the aim of this study was to determine the influence of urbanization on subsurface warming, the authors applied the same initial values for the past as the present to exclude the effects of global warming.

3. Result and discussion

3.1. Numerical simulations of surface temperature (T_{sfc})

From the numerical modeling outputs for each city, the authors examined the distribution of T_{sfc} (variations at 0.5 cm below ground level) and its diurnal variations (Figs. 3–5 show the examples for Bangkok, Seoul, Taipei, and Jakarta,). Results show that: In Bangkok at 3 AM on the analyzed day in 1910 (Fig. 3), T_{sfc} in the city center and riverside area along the Chao Phraya was 301 K with hot spots of up to 303 K. T_{sfc} in the suburbs was 298 K over broad areas, and the sea surface temperature remained at 303 K (input initial temperature). At 3 AM in 2000, the area of high temperature in the city center is not well defined and the newly urbanized northern suburbs show warming to 303 K. At 3 PM in 1910, T_{sfc} in the city center is 324 K and is surrounded by a broad area of around 313 K, and the sea surface and cool spots along the Chao Phraya river show T_{sfc} of 303 K. At 3 PM in 2000, the area of high temperature at the city center is again not well defined and the northern suburbs show warming to 329 K.

In the modeling presented here, each of the seven megacities showed T_{sfc} to be increasing by about 1.1 K 100 y^{-1} during the 20th

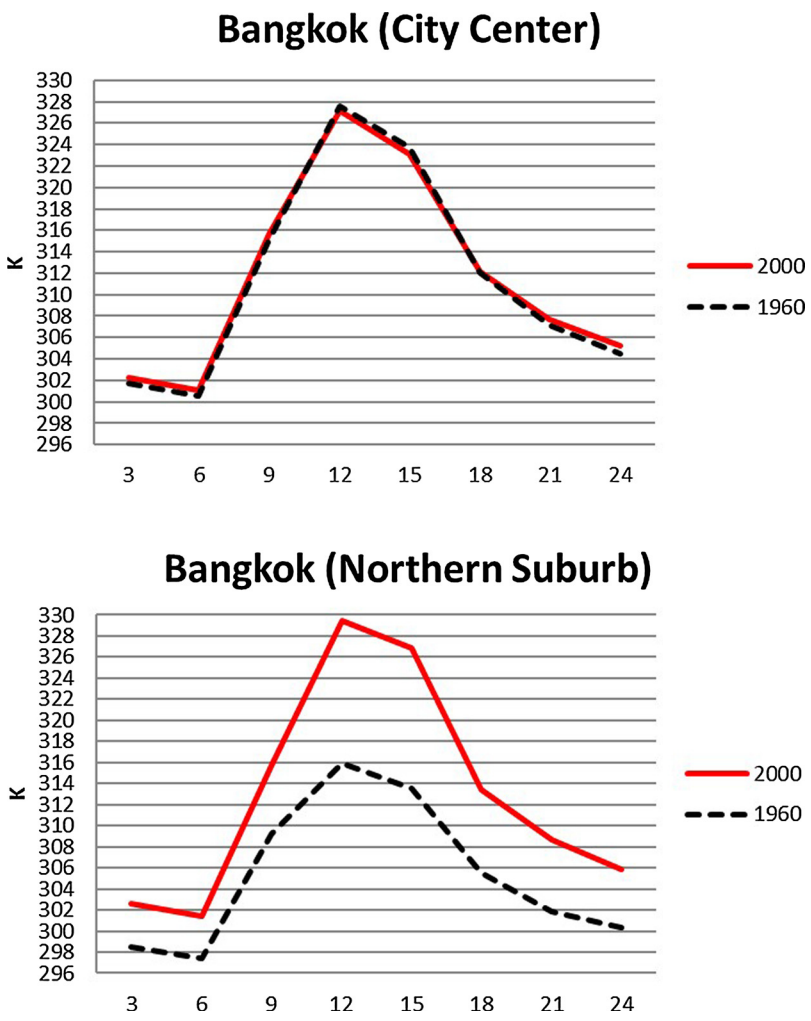

Fig. 4. Diurnal variability of computed T_{sfc} in the hottest season (calm and clear day) in two stages. *Note: Difference of computed warming of T_{sfc} in the same term (Bangkok).*

century (modeling based on a calm and clear day of the hottest season; Fig. 5; Table 2), despite the diversity among cities of both the stage of urbanization and the observed subsurface temperature profiles (Taniguchi et al., 2007; Taniguchi, Burnett, & Ness, 2009b). Surface warming reported during the last century in the city centers of Tokyo and Bangkok (Table 3) were 2.8 °C and 1.8 °C, respectively (Taniguchi et al., 2007; Taniguchi, Burnett, & Ness, 2009b). These rates of warming in the city centers are similar because both megacities were already urbanized at the beginning of the 20th century (Fig. 1). For example, there is almost no difference between the graphs of diurnal change of T_{sfc} between 1960 and 2000 in the city center of Bangkok (Fig. 4), whereas in the northern suburbs of Bangkok, where land use between 1960 and 2000 has changed from rice paddy to urban, there has been a rapid increase of T_{sfc}. In particular, T_{sfc} in the northern suburbs of Bangkok in 2000 was higher than in 1960, by about 15 K in the daytime and by about 5 K at dawn. Thus, it appears that subsurface temperature profiles differ according to the start time of periods of urbanization.

3.2. Accounting for seasonal variability

The annual variations of T_a and the percentage of rainy days each month are considerable in the seven megacities (Fig. 6). Annual ranges of T_a are smallest for low-latitude cities such as Jakarta, Manila, and Bangkok, but are much larger in Taipei and megacities farther north, particularly in Seoul where the deviation is around 30 °C. The percentage of rainy days in Jakarta (southern hemisphere) is lowest in August and highest in February, whereas in Manila and Bangkok (northern hemisphere), August is in the rainy season. Osaka receives most of its rainfall from February to April. The monthly percentage of rainy days in Taipei (35%–60% throughout the year) is the most consistent of the megacities considered here.

Annual average values of T_{sfc} can be derived from subsurface temperature profiles, but annual variations of meteorological factors such as T_a and the percentage of rainy days have a considerable effect on the modeling result. It is therefore preferable to simulate entire years (rather than a single period of 48 h within each year) to account for these variations. Because of limited computer resources and computing time, a less resource-hungry method is needed. To attempt to account for seasonal climate variability, simulations were run for three additional cases (rainy day, clear day in the coldest or rainy season, and rainy day in the coldest or rainy season) for each year in each megacity (Fig. 7; Table 1). The average of these three cases and the base case (clear day in the hottest season) was considered to be the 'pseudo-annual' average (Table 3). The percentage of days of each weather type in each season was used in the calculation of these pseudo-annual averages. By using this methodology (weighting the averages according to the percentages), it is possible to account for the differences of seasonal climatic variability in megacities in both middle latitudes (temperate zone) and low latitudes (tropical zone). In this study, only the effects of anthropogenic heat and land-use change are considered. According to the results of Ichinose et al. (1999), the ratio of warming effects of land-use change to the ones of anthropogenic heat is about 1:2 for the case of

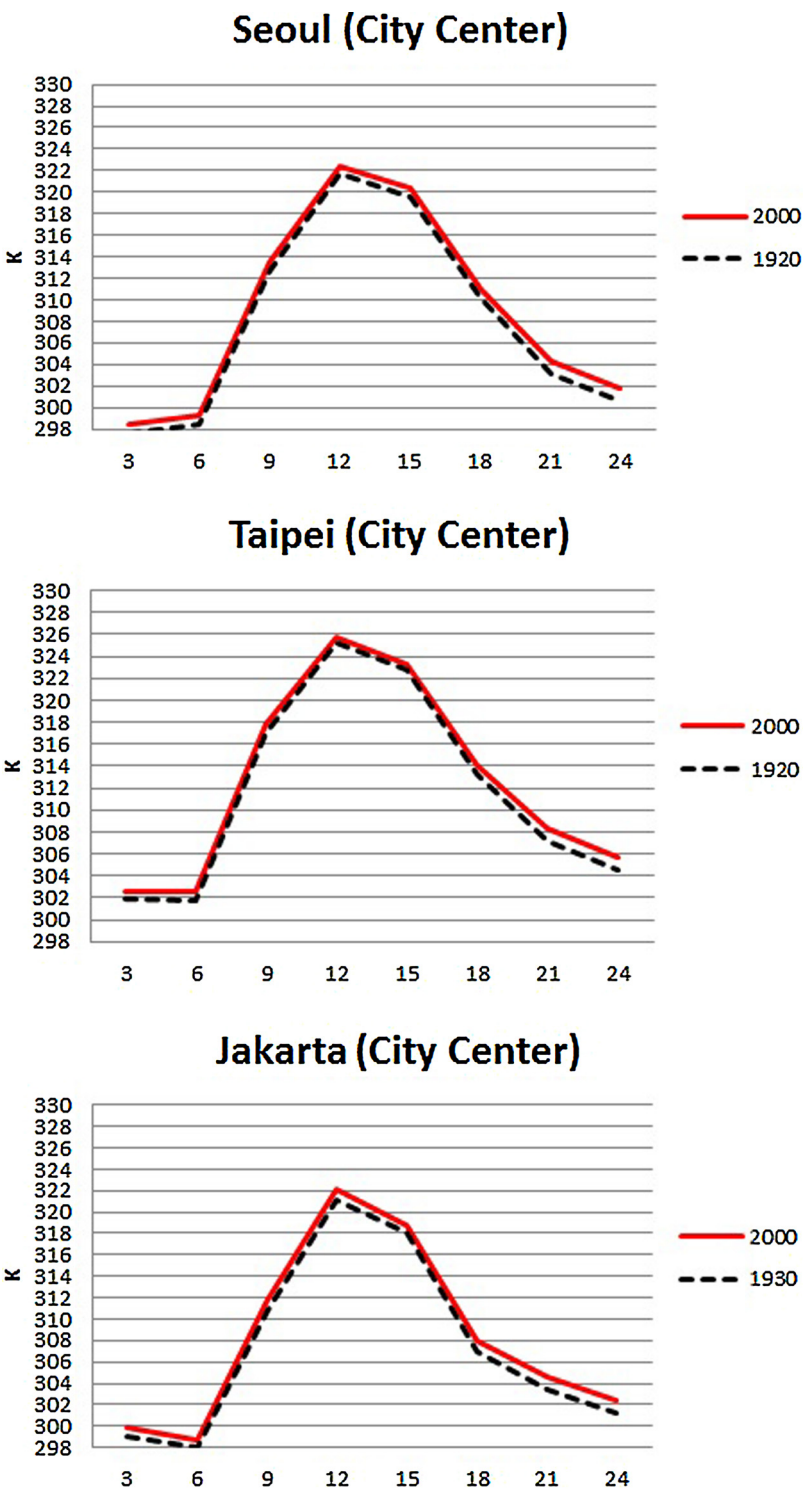

Fig. 5. Diurnal variability of computed T_{sfc} in the hottest season (calm and clear day) in two stages.

central Tokyo. The difference between modeled and observed values can be read from Table 3. Global or regional warming effects are ignored here, otherwise the interpretation of Table 3 would become very complex. This ignorance brought the difference shown in Table 3.

The difference between the rates of change of T_{sfc} in Bangkok (0.9 K 100 y^{-1}) and Tokyo (1.9 K 100 y^{-1}) is considerable, which suggests that differences of annual climatic variability are important in analyses of urban subsurface warming. In particular, increases of T_{sfc} in the coldest season in the northern cities make a larger contribution to subsurface warming than in the south. For example in Seoul, the northernmost city with the greatest annual range of T_a, the differences of T_{sfc} in the cooler seasons between 1920 and 2000 (Fig. 7) are substantial. In Jakarta, however, where the seasonal variability of T_a is much smaller, the difference of T_{sfc} is affected only by the weather (rainy or fine).

4. Conclusion

The authors used a mesoscale climate model and digital land-use data from seven Asian megacities to simulate T_{sfc} for three discrete

Table 2
Warming of T_{sfc} (daily average of a calm and clear day in the hottest season) at the city center of each Asian megacity in the 20th Century.

	K y^{-1}	Julian day
Seoul	0.011	210
Tokyo	0.011	210
Osaka	0.012	210
Taipei	0.010	210
Bangkok	0.009	90
Manila	0.010	90
Jakarta	0.013	210

Table 3
Warming of T_{sfc} in consideration of seasonal climate variability (pseudo-annual average) and comparison to observed subsurface temperature (Taniguchi et al., 2007; Taniguchi, Burnett, & Ness, 2009b).

	Computed value (K 100 y^{-1})	Observed value (K 100 y^{-1})
Seoul	1.67	2.5
Tokyo	1.93	2.8
Osaka	1.87	2.2
Taipei	1.00	No data
Bangkok	0.90	1.8
Manila	1.12	No data
Jakarta	0.60	1.2

years of the 20th century. They used them in numerical simulations of urban subsurface warming related to recent urbanization in the seven cities. The variability of T_{sfc} simulated by using these data as surface boundary conditions was compared with the measured vertical profiles of subsurface temperature in the targeted megacities, which were expected to record the historical time-series of T_{sfc}. In the modeling on a calm and clear day of the hottest season, each of the seven megacities showed T_{sfc} to be increasing by about 1.1 K 100 y^{-1} during the 20th century, despite the diversity among cities of both the stage of urbanization and the observed subsurface temperature profiles. These rates of warming in the city centers are similar because both megacities were already urbanized at the beginning of the 20th century. To attempt to account for seasonal climate variability, simulations were run for three additional cases (rainy day, clear day in the coldest or rainy season, and rainy day in the coldest or rainy season) for each year in each megacity. The average of these three cases and the base case was considered to be the 'pseudo-annual' average. The percentage of days of each weather type in each season was used in the calculation of these pseudo-annual averages. The difference between the rates of change of T_{sfc} in Bangkok (0.9 K 100 y^{-1}) and Tokyo (1.9 K 100 y^{-1}) is considerable, which suggests that differences of annual climatic variability are important in analyses of urban subsurface warming. So the authors conclude historical digital land-use data are useful to study past urban climate change in numerical simulation, and difference of annual climatic variability brings the difference of subsurface warming in each mega-city.

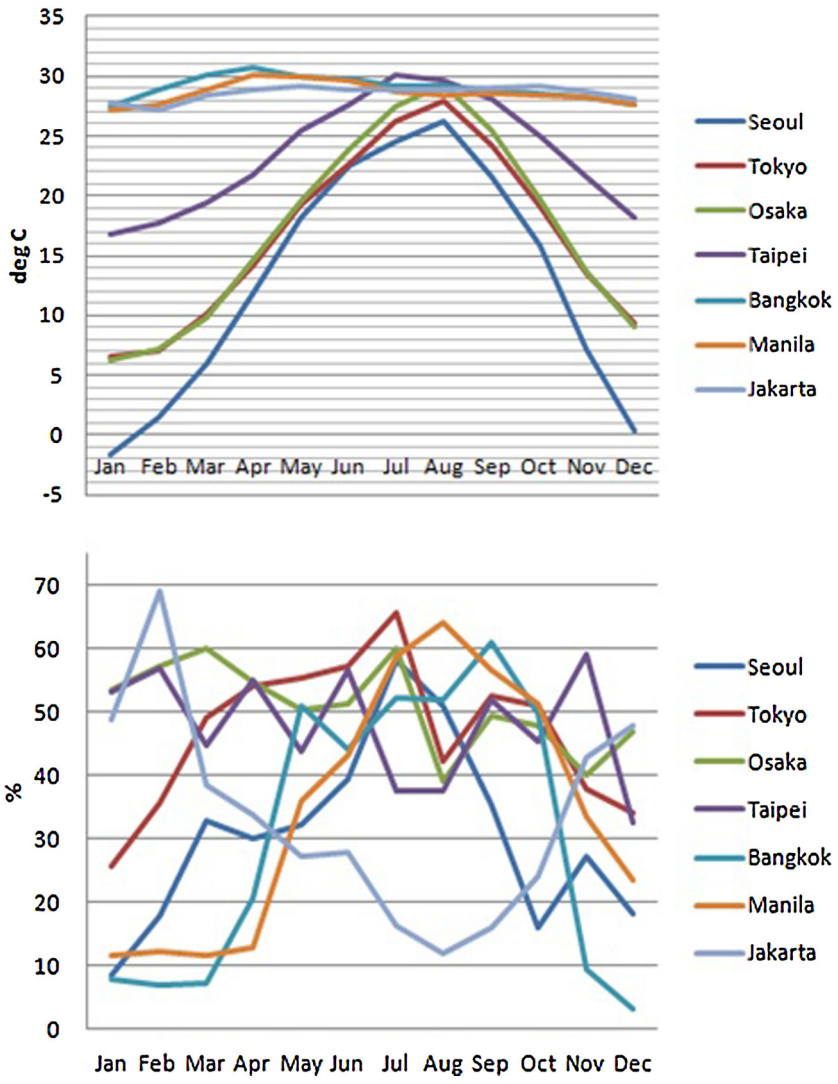

Fig. 6. Annual variability of T_a (upper) and percentage of rainy days (lower).

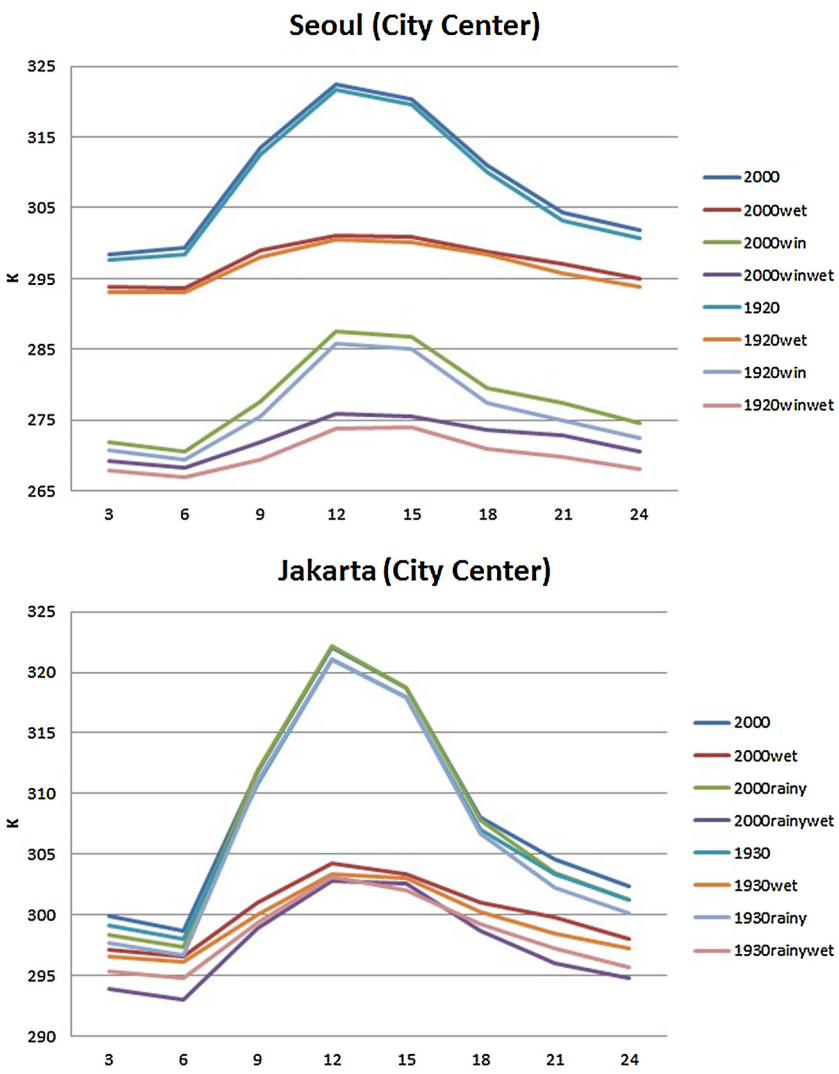

Fig. 7. Diurnal variability of computed T_{sfc} in two stages. *Note: Base case is the hottest season (or the dry season) and clear day. "wet": rainy day, "win": the coldest season, "rainy": the rainy season.*

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